

Observational Evidence of Convective Cycles as the Cause of the Blazhko Effect in RR Lyrae Stars

RICHARD B. STOTHERS

NASA Goddard Institute for Space Studies, New York, NY 10025; rstothers@giss.nasa.gov

Received 2009 September 9; accepted 2010 March 22; published 2010 April 16

ABSTRACT. Among RR Lyrae stars displaying the Blazhko effect, a few show no period modulation in spite of striking changes in their light amplitudes. This anomalous behavior and the mean period of the affected variables are predicted correctly by the theory of slow convective cycles in the stellar envelope.

1. INTRODUCTION

A small cyclic variability of the pulsation period of RR Lyrae stars was first discovered by Blazhko (1907) in RW Dra. Shapley (1916) confirmed the existence of cyclic period variations in RR Lyr itself and detected also a change in the shape and amplitude of its light curve around the time of maximum light. We know today of RR Lyrae stars with no cyclic period variability, yet with large cyclic changes in both light and velocity amplitudes. This paradox must be telling us something important about the phenomenon that is now called the Blazhko effect. The key appears to be the behavior of the pulsation period, which is a simple, purely dynamical quantity, rather than of the amplitude, which depends sensitively on the complex thermal properties of the stellar envelope.

For many years the observed modulations have usually been interpreted as being due either to modal resonances involving two close periods or to the changing aspect of a magnetic oblique rotator-pulsator. Pros and cons of these various theories have been much reviewed recently (e.g., Chadid & Chapellier 2006; Kolenberg & Bagnulo 2009), with a great deal of doubt being cast observationally on the validity of these classes of explanations. Nonetheless, linear nonadiabatic pulsational models with unstable, or marginally stable, nonradial modes close in period to the fundamental radial mode have been constructed (Cox 1993, 2009), although it is not yet known whether the nonradial modes would reach sufficient amplitude to be observationally important.

To explain the observed period variability, we have recently proposed that turbulent convection in the stellar envelope, where the pulsations mostly take place, becomes cyclically strengthened and weakened on a time scale that is long compared to the pulsation period (Stothers 2006). Linear and nonlinear models of RR Lyrae stars show that a buildup of convection will increase the pulsation period in the hotter stars and decrease it in the cooler ones. Although the crossover effective temperature depends on both mass and luminosity, its mean value probably lies somewhere around ~ 6400 K, corre-

sponding to a period of ~ 0.5 day for Bailey type *ab* variables (fundamental-mode pulsators).

What might cause such a cyclic modulation of convection? We have suggested a solarlike magnetic cycle, wherein a turbulent or rotational dynamo creates a magnetic field that then decays due to convective shredding of the stretched field lines with concomitant ohmic losses. Since a growing magnetic field is expected to weaken convection while a decaying one strengthens it, we have a plausible mechanism for the proposed convection cycles. These might be more regular than in the case of the Sun, because the large-amplitude pulsational motions of an RR Lyrae star and the associated convective disturbances during a single pulsation period may well act as a metronome controlling the regularity of the Blazhko cycle. Like the magnetoconvective dynamo in the Sun, additional periods of even greater length can also be expected to occur. More details of our magnetic idea can be found in our earlier article. The predicted magnetic field strengths are too small to alter the pulsation period to any great extent, nor would the changing pulsation amplitudes alter the period very much (Stothers 1980, 2006; Jurcsik et al. 2008b); therefore, the observed period modulation should provide a relatively clean test for the convection cycles.

What about the observed simultaneous changes of the pulsation amplitudes? This is a tricky problem because convection reduces the amplitudes in nonlinear models of RR Lyrae stars (Deupree 1977; Stellingwerf 1984; Gehmeyr 1992; Feuchtinger 1999; Di Criscienzo et al. 2004) while at the same time pulsation weakens convection (Christy 1964; Feuchtinger 1999), an effect that works in the opposite direction. It is not entirely certain that under all circumstances a reduction of the amplitudes would prevail, and so we will not pursue this issue further here. Some evidence drawn from published studies of RR Lyr and RZ Lyr has tended to support our basic theoretical ideas (Stothers 2006). More recently, Jurcsik et al. (2008a) observed MW Lyr over a complete Blazhko cycle, and found (as we had predicted) only a single radial oscillation mode rather than two or more interacting modes. Moreover, the light amplitude of MW Lyr varied symmetrically about the mean during the Blazhko cycle,

again as predicted. We had, however, regarded as a significant flaw in our purely radiative nonlinear models of RR Lyrae stars the fact that minimum light at half-amplitude during a hypothetical Blazhko cycle was as much brighter as maximum light was fainter. This apparent problem certainly still exists in the case of such classic variables as RR Lyr, RZ Lyr, and XZ Cyg, that show stable light minima, but many other Blazhko variables resemble MW Lyr in this respect. On the other hand, the published radial-velocity curves of RR Lyr, RZ Lyr, XZ Cyg, and TY Gru all display symmetrically varying maxima and minima throughout the Blazhko cycle (Struve & van Hoof 1949; Preston et al. 1965; Romanov 1977; Preston et al. 2006). These radial-velocity observations, therefore, warn us not to trust the predicted amplitudes of the theoretical light curves very much.

The clearest signature of the convection cycles is expected to be the observed behavior of the pulsation period during a Blazhko cycle. Our purpose here is to examine this behavior in the case of the best-observed RR Lyrae stars and to compare the observations quantitatively with the predictions of our theory more fully than in our earlier paper. This is only an exploratory study, but is believed to be sufficient to test the theory's fundamental prediction.

2. OBSERVED BLAZHKO VARIABLES

Recognized Blazhko variables have been listed by Szeidl (1976, 1988) with corrections and updates subsequently published by Smith (1995), Sódor & Jurcsik (2005), Jurcsik et al. (2005), Wils & Sódor (2005), and others. We have reviewed the available data for type *ab* variables showing large modulation amplitudes, and have listed in Table 1 those variables showing negligible period variation. The pulsation period P_0 and Blazhko period P_B are also tabulated.

The stars of Table 1 exhibit a mix of metallicities, although most are relatively metal-poor (Smith 1995). At the level of discrimination attainable in this article, it is not possible to discern any noticeable metallicity effect, and so we will treat all these

stars statistically as being “metal-poor.” This will be acceptable for averaging purposes.

3. THEORETICAL MODELS

The theoretical models on which we have based our conclusions are taken from a previous paper (Stothers 2006), but are here summarized in Table 2. Pulsation periods of the models have been calculated by using linear nonadiabatic theory applied to the stellar envelope. The quantity $\delta P/P$ represents the relative change of the fundamental-mode period between a purely radiative model with $\alpha = 0$ and a fully convective model with $\alpha = 2$, where α is the ratio of convective mixing length to local pressure scale height (the sign of $\delta P/P$ is in the sense of convective model minus radiative model). It is important to emphasize that the comparison of radiative and convective models must be done with exactly the same input physics and same computer program; only α should be allowed to vary. The reason is that any extraneous effects (such as comparing the periods of linear and nonlinear models) can overwhelm the small change of period caused only by convection. Since very similar results have been found by several other authors using full-amplitude nonlinear models with different opacities, chemical compositions, and convection theories from ours (see the review in Stothers 2006), the results presented in Table 2 are believed to be quite robust. Because convection in these stellar envelopes arises from the partial ionization of hydrogen and helium, the effect of metallicity on convection (through the opacity) and hence on the periods should be unimportant.

The variation of $\delta P/P$ with a change of any model parameter, such as stellar mass, luminosity, or effective temperature, turns out to be monotonic, and, in logarithmic form, approximately linear over the specific ranges of interest here. Therefore, to proceed further, we fit the data of Table 2 to two linear equations—one for $\log P_0$ and the other for $\delta P/P$ —in the quantities $\log M$, $\log L$, and $\log T_e$. Between these two equations we eliminate $\log \log T_e$ and then set $\delta P/P = 0$.

TABLE 1
BLAZHKO VARIABLES WITH LARGE AMPLITUDE MODULATION AND NEGLIGIBLE PERIOD VARIATION

Star	P_0 (day)	P_B (day)	Reference
AQ Lyr	0.357	65	Jurcsik et al. 2009
S Ara	0.452	49	Chadid et al. 2009
UZ Vir	0.459	68	Jurcsik et al. 2009
RV UMa	0.468	90	Balazs & Detre 1957; Nagy 1998; Hurta et al. 2008
XZ Dra	0.476	76	Jurcsik et al. 2002
FM Per	0.489	122	Lee & Schmidt 2001
SS For	0.495	35	Kolenberg et al. 2009
RZ Lyr	0.511	117	Romanov 1967; Tsesevich 1969
MACHO 82.8410.55	0.515	86	Kurtz et al. 2000
AF Vel	0.527	59	Wils & Sódor 2005
UV Oct	0.543	145	Wils & Sódor 2005
RV Cet	0.623	112	Wils & Sódor 2005

TABLE 2
THEORETICAL MODELS OF RR LYRAE STARS

M/M_{\odot}	$\log(L/L_{\odot})$	$\log T_e$	P_0 (day)	$\delta P/P$
0.578	1.585	3.813	0.533	+0.001
0.679	1.585	3.813	0.479	-0.020
0.578	1.800	3.813	0.810	+0.004
0.578	1.585	3.792	0.631	-0.022

The result is

$$\log P_0 = -2.066 - 1.624 \log(M/M_{\odot}) + 0.891 \log(L/L_{\odot}). \quad (1)$$

This is our predicted relation between mass, luminosity, and pulsation period for any Blazhko variable with negligible period variation. Corresponding effective temperatures are given by

$$\log T_e = 3.897 + 0.274 \log(M/M_{\odot}) - 0.013 \log(L/L_{\odot}). \quad (2)$$

4. RR LYRAE MASSES AND LUMINOSITIES

The masses and luminosities of RR Lyrae stars have been much investigated, but are still rather uncertain. By fitting a secondary bump on the velocity and light curves of RR Lyr and RR Cet to the predictions from theoretical nonlinear models, it has been possible to infer a mass of $\sim 0.65 M_{\odot}$ (Hubickyj & Stothers 1986) using the method of Christy (1966). This method is mostly sensitive to the mass, showing little dependence on luminosity and effective temperature, but it is also sensitive to the adopted opacities (Stothers 1981), which should be updated in any new study. The Bailey type *c* variables (first-overtone pulsators) do not show any such bump, but a matching of theoretical and observed phases of some other diagnostic features in the velocity and light curves in the case of four metal-poor type *c* field variables reveals a constancy of their luminosity-to-mass ratios, $L/M = 70$ solar units (Hubickyj & Stothers 1986). This uniform ratio implies $\log(L/L_{\odot}) = 1.66$ if the type *ab* and type *c* variables have similar mean masses and mean luminosities.

Simon & Clement (1993) have determined from a new set of theoretical models that the Fourier parameters of the light curves, notably the phase angle ϕ_{31} , can be used to infer the masses and luminosities of type *c* variables at a given period. They have estimated that an error of ± 0.1 in ϕ_{31} translates into an error of ± 0.025 in $\log(M/M_{\odot})$ and ± 0.035 in $\log(L/L_{\odot})$. Since the typical uncertainties of the observed values of ϕ_{31} are 0.3–0.4, this method implies a rather large uncertainty in the derived values of mass and luminosity. Nevertheless, using this method, Arellano Ferro et al. (2006) have listed 14 published values of mean masses and mean luminosities for the type *c* variables in 12 Galactic globular clusters. M/M_{\odot} ranges from

0.53 to 0.76 and $\log(L/L_{\odot})$ from 1.65 to 1.81, depending on metallicity; the ensemble averages are 0.61 and 1.74, respectively.

Simon (1985) and Simon & Aikawa (1986) found that ϕ_{31} for the type *ab* variables is very poorly predicted by theoretical models. Nevertheless, a purely observational correlation between ϕ_{31} , period, and visual absolute magnitude has been demonstrated by Kovács & Jurcsik (1996) for the type *ab* variables in a number of globular clusters; the zero point of the absolute magnitudes was assigned from the Baade-Wesselink luminosities compiled by Clementini et al. (1995). Determinations for a total of 10 Galactic globular clusters, as listed by Arellano Ferro et al. (2006), have led to an average of $M_V = 0.76$ —or $\log(L/L_{\odot}) = 1.61$ using a mean bolometric correction of −0.03 (Sandage & Cacciari 1990). However, this method is very sensitive to the uncertainties of both ϕ_{31} and the Baade-Wesselink luminosities. Therefore, we take a mean of the values for the type *c* and type *ab* variables based on ϕ_{31} : $\log(L/L_{\odot}) = 1.67$.

This mean value is in excellent agreement with more direct methods of deriving the luminosity. A large number of luminosity determinations for metal-poor RR Lyrae stars have been made by using secular or statistical parallaxes, the Baade-Wesselink method, the moving cluster method, and cluster main-sequence fitting. Twenty such determinations have yielded an average $M_V = 0.61 \pm 0.15$ (Stothers 1983). Although the number of published determinations has now increased somewhat, the simple law of large numbers suggests that the above mean value would change very little. This is confirmed by the studies of Sandage & Cacciari (1990), Smith (1995), and Gratton et al. (2003). Accordingly, by using the same average bolometric correction, we find $\log(L/L_{\odot}) = 1.67$. This value also agrees exactly with what Cox (1995) got by using only well-observed periods, apparent magnitudes, and pulsation theory for the RR Lyrae stars in two typical metal-poor globular clusters, M3 and M5. It also agrees closely with the Hubickyj & Stothers (1986) luminosity value.

As for the average mass of RR Lyrae stars, we note the Fourier decomposition mass of $0.61 M_{\odot}$ for the type *c* variables and the bump mass of $0.65 M_{\odot}$ for the type *ab* variables. Unfortunately, the pulsation constant method, using the (period, mean density) relation, shares the serious drawback of the Baade-Wesselink method for getting luminosities in requiring accurate knowledge of the effective temperature. Since $L \sim R^2 T_e^4$ and $M \sim P^{-1/2} L^{3/2} T_e^{-6}$, the derived results are accordingly much less reliable (Sandage 1993; Jurcsik 1998) and so will not be used here. The period ratio method for the double-mode (fundamental mode and first overtone) pulsators, sometimes called the “Petersen diagram” method, depends on P_1/P_0 as a function of P_0 , M/M_{\odot} , and chemical composition. Using up-to-date opacities, Cox (1995) derived an average $M/M_{\odot} = 0.73 \pm 0.03$ for the type *d* variables in a small number of Galactic globular clusters. Sensitivity to the metallicity, however, suggested to Cox that the true error could be as large as ± 0.05 . Such high masses

derived from the period ratio method have persisted in many subsequent studies (e.g., Bragaglia et al. 2001; Clementini et al. 2004). Since none of the available methods of deriving the mass has high accuracy, we simply average the three determinations given above and accordingly adopt $M/M_{\odot} = 0.66 \pm 0.03$.

5. TEST OF THE THEORY

Our theoretical models conveniently bracket the observed mean luminosity and mean mass of RR Lyrae stars, as just given. Introducing $\log(L/L_{\odot}) = 1.67$ and $M/M_{\odot} = 0.66$ into equation (1) yields a predicted mean pulsation period of 0.52 day for the Blazhko variables with negligible period variation. This agrees closely with the observed mean period of 0.49 day. Such surprisingly close agreement appears all the more remarkable when one considers the uncertainties entering into the estimations of $\log(L/L_{\odot})$ and M/M_{\odot} . However, we are here dealing with averages of a large amount of data, where the random errors tend to cancel out, and especially with averages based on different methods of analysis, where the systematic errors themselves tend to cancel out. Individual stellar differences of luminosity, mass, and metallicity will wash out in the averages. According to equations (1) and (2), the effective temperature corresponding to $P_0 = 0.49$ day and $\log(L/L_{\odot}) = 1.67$ is 6700 K.

There was no way of knowing beforehand whether any theoretical models would have $\delta P/P = 0$, let alone what their corresponding pulsation periods would be. Therefore, this successful prediction of the theory must be regarded as highly significant.

Individual stars, of course, will deviate from the average. The observed range of pulsation periods for the 12 listed stars with

$\delta P/P = 0$ is 0.36–0.62 day. Although all known Blazhko variables with large amplitude modulation cover a greater range of 0.29–0.73 day, most stars lie between 0.37 and 0.62 day, as do type *ab* stars generally (Smith 1995; Jurcsik et al. 2005; Wils & Sóder 2005). The happenstance that the midpoint of this range occurs not far from the mean period of the variables with $\delta P/P = 0$ does not detract from the striking agreement between theory and observation at ~ 0.50 day.

6. CONCLUSION

The main conclusions to be drawn from the results of our test for convection cycles in RR Lyrae stars are the following:

1. The mean pulsation period, 0.49 day, of the 12 listed Blazhko variables with negligible period modulation is essentially correctly predicted by the new theory. The probability of this occurring by chance is very small.
2. This agreement lends support to the observationally (or semiempirically) determined values of mean mass and mean luminosity for metal-poor RR Lyrae stars, namely, $M/M_{\odot} = 0.66 \pm 0.03$ and $\log(L/L_{\odot}) = 1.67$.

The success of the present test suggests that it would now be worthwhile to study in detail the combinations of mass and luminosity that lead to models with $\delta P/P = 0$ over the whole period range of observed RR Lyrae stars.

The critical and extensive comments by two anonymous referees have substantially improved the content of this article, especially one referee's numerous additions to Table 1.

REFERENCES

- Arellano Ferro, A., García Lugo, G., & Rosenzweig, P. 2006, Rev. Mex. AA, 42, 75
- Balazs, J., & Detre, L. 1957, Mitt. Sternw. Ungar. Akad. Wiss., 34, 1
- Blazhko, S. 1907, Astron. Nachr., 175, 325
- Bragaglia, A., Gratton, R. G., Carretta, E., Clementini, G., Di Fabrizio, L., & Marconi, M. 2001, AJ, 122, 207
- Chadid, M., & Chapellier, E. 2006, A&A, 456, 305
- Chadid, M., et al. 2009, in AIP Conf. Proc. 1170, Stellar Pulsation: Challenges for Theory and Observation, ed. J. A. Guzik, & P. A. Bradley (Santa Fe: AIP), 299
- Christy, R. F. 1964, Rev. Mod. Phys., 36, 555
- . 1966, ApJ, 144, 108
- Clementini, G., Caretta, E., Gratton, R., Merighi, R., Mould, J. R., & McCarthy, J. K. 1995, AJ, 110, 2319
- Clementini, G., Corwin, T. M., Carney, B. W., & Sumerel, A. N. 2004, AJ, 127, 938
- Cox, A. N. 1993, in IAU Colloq. 139, New Perspectives on Stellar Pulsation and Pulsating Variable Stars, ed. J. M. Nemec, & J. M. Matthews (Cambridge: Cambridge Univ. Press), 409
- . 1995, in ASP Conf. Ser. 78, Astrophysical Applications of Powerful New Databases, ed. S. J. Adelman, & W. L. Wiese (San Francisco: ASP), 243
- . 2009, in AIP Conf. Proc. 1170, Stellar Pulsation: Challenges for Theory and Observation, ed. J. A. Guzik, & P. A. Bradley (Santa Fe: AIP), 276
- Deupree, R. G. 1977, ApJ, 211, 509
- Di Criscienzo, M., Marconi, M., & Caputo, F. 2004, ApJ, 612, 1092
- Feuchtinger, M. U. 1999, A&A, 351, 103
- Gehmeyr, M. 1992, ApJ, 399, 272
- Gratton, R. G., et al. 2003, A&A, 408, 529
- Hubickyj, O., & Stothers, R. B. 1986, ApJ, 309, 122
- Hurta, Z., Jurcsik, J., Szeidl, B., & Sóder, A. 2008, AJ, 135, 957
- Jurcsik, J. 1998, A&A, 333, 571
- Jurcsik, J., Benkó, J. M., & Szeidl, B. 2002, A&A, 396, 539
- Jurcsik, J., Szeidl, B., Nagy, A., & Sóder, A. 2005, Acta Astron., 55, 303
- Jurcsik, J., et al. 2008a, MNRAS, 391, 164
- . 2008b, MNRAS, 393, 1553
- . 2009, MNRAS, 400, 1006
- Kolenberg, K., & Bagnulo, S. 2009, A&A, 498, 543
- Kolenberg, K., et al. 2009, MNRAS, 396, 263
- Kovács, G., & Jurcsik, J. 1996, ApJ, 466, L17
- Kurtz, D. W., et al. 2000, in ASP Conf. Ser. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, ed. L. Szabados, & D. W. Kurtz (San Francisco: ASP), 291

- Lee, K. M., & Schmidt, E. G. 2001, PASP, 113, 835
- Nagy, A. 1998, A&A, 339, 440
- Preston, G. W., Smak, J., & Paczyński, B. 1965, ApJS, 12, 99
- Preston, G. W., Thompson, I. B., Sneden, C., Stachowski, G., & Shectman, S. A. 2006, AJ, 132, 1714
- Romanov, Y. 1967, Inf. Bull. Variable Stars, 205, 1
- _____. 1977, Perem. Zvezdy, 20, 299
- Sandage, A. 1993, AJ, 106, 703
- Sandage, A., & Cacciari, C. 1990, ApJ, 350, 645
- Shapley, H. 1916, ApJ, 43, 217
- Simon, N. R. 1985, ApJ, 299, 723
- Simon, N. R., & Aikawa, T. 1986, ApJ, 304, 249
- Simon, N. R., & Clement, C. M. 1993, ApJ, 410, 526
- Smith, H. A. 1995, RR Lyrae Stars (Cambridge: Cambridge Univ. Press)
- Sóðor, A., & Jurcsik, J. 2005, Inf. Bull. Variable Stars, 5641, 1
- Stellingwerf, R. F. 1984, ApJ, 284, 712
- Stothers, R. B. 1980, PASP, 92, 475
- _____. 1981, ApJ, 247, 941
- _____. 1983, ApJ, 274, 20
- _____. 2006, ApJ, 652, 643
- Struve, O., & van Hoof, A. 1949, ApJ, 109, 215
- Szeidl, B. 1976, in Multiple Periodic Variable Stars, ed. W. S. Fitch (Dordrecht: Reidel), 133
- _____. 1988, in Multimode Stellar Pulsations, ed. G. Kovács, L. Szabados, & B. Szeidl (Budapest: Konkoly Obs.), 45
- Tsesevich, V. P. 1969, RR Lyrae Stars (Jerusalem: IPST)
- Wils, P., & Sóðor, A. 2005, Inf. Bull. Variable Stars, 5655, 1